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Top Quark Physics at the Tevatron

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The heaviest known elementary particle, the top quark, was discovered in 1995 by the CDF and D0 collaborations at the Tevatron proton-antiproton collider at Fermilab. Since its discovery, a large program was set in motion by the CDF and D0 collaborations to characterize the production and decay properties of top quarks, and investigate their potential for searches of new phenomena beyond the standard model. During the past 20 years, new methods were developed and implemented to improve the measurements and searches for new physics in the top-quark sector. This article reviews the achievements and results obtained through studies of the top quark at the Tevatron.

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1. Introduction

The top quark (t) was discovered in 1995 by the CDF and D0 collaborations at the Tevatron proton antiproton ($p\bar{p}$) collider at Fermilab.[1,2] With a mass of $m_t = 173.2 \pm 0.9$ GeV,[3] the top quark is the heaviest known elementary particle, which has led to speculations that it may play a special role in the mechanism of

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electroweak symmetry breaking. The lifetime of the top quarks is shorter than their hadronization time, which provides a unique opportunity to study the properties of essentially bare quarks. Since its discovery, intensive programs have been undertaken at the CDF and D0 experiments, and recently at the LHC, to categorize the properties of the newly discovered particle, believed to be the top quark of the standard model of particle physics (SM). In particular, the production and properties are studied and compared to predictions from SM calculations, and searches for physics beyond the SM (BSM) in the top-quark sector have been performed through comparisons of decay modes and departures from expectations in different final states. This review presents the status of our understanding of the top quark that has been gained from experiments at the Tevatron.

1.1. *A brief History of the Top Quark*

One of the greatest legacies of the Tevatron is the observation of the top quark. The existence of the top quark was predicted years before its discovery.[4,5] After the discovery of the τ-lepton at SLAC in 1976, and the upsilon, and thereby the b-quark, in 1977 at Fermilab, the fermion sector of the SM had to be extended from two to three generations. Since the SM predicted a doublet for each quark generation, the up-type partner of the b-quark, i.e., the top quark, was missing. Based on this realization, a race was launched to find the predicted top quark, first, in searches for $t\bar{t}$ bound states, as, for example, at the e^+e^- colliders PETRA at DESY and at Tristan at KEK. Next, the top quarks were sought in W-boson decays ($W \to tb$) at the UA1 and UA2 experiments at CERN. In 1988, CDF joined the race to find the top quark in the initial running phase of the Tevatron, and D0 joined CDF for Run I in 1992. (Run I lasted from 1992 to 1996, colliding p and $\bar{p}$ at a center-of-mass energy of 1.8 TeV, and collecting about 100 pb^{-1} of data per experiment.) Due to different designs of the CDF and D0 detectors during Run I, the experiments used different strategies in their searches for the top quark in the $p\bar{p} \to t\bar{t}$ final state. CDF focused on b-jet identification to reduce background, and D0 on the use of topological information. The first searches at the Tevatron set lower limits on the mass of the top quark that were above the mass of the W boson, eliminating the possibility of observing the top quark via decays of W-bosons. It took until 1994 however to find first evidence for possible $t\bar{t}$ production[6,7]. Definitive evidence for the observation of the top quarks was presented on February 24th, 1995, when CDF and D0 simultaneously submitted their results for publication.[1,2] The observations were based on 50 pb^{-1} at D0, and 67 pb^{-1} at CDF. After the first observation of top quarks in $t\bar{t}$ events, it took 14 more years until the electroweak (EW) production of single top quarks was reported by the CDF and D0 collaborations[8,9,10] during Run II, which lasted from 2001 until 2011, with data taken at a $p\bar{p}$ center-of-mass energy of 1.96 TeV, recording about 10 fb^{-1} of integrated luminosity per experiment.

2. Production and Decay in the Standard Model

At hadron colliders, top quarks are expected to be produced mainly as $t\bar{t}$ pairs through the quantum-chromodynamic (QCD) strong interaction, with quark-antiquark annihilation ($q\bar{q} \to t\bar{t}$) and gluon fusion ($gg \to t\bar{t}$) corresponding to the primary processes. At the Tevatron, $q\bar{q}$ is responsible for $\approx 85\%$ of the total $t\bar{t}$ production cross section. The latest calculations, at next-to-next-to-leading order (NNLO) in perturbative QCD for the $q\bar{q} \to t\bar{t}$ component, and at approximate NNLO for $gg \to t\bar{t}$, both including soft-gluon resummations to next-to-next-to-leading logarithmic (NNLL) accuracy, yield a total cross section of $\sigma(p\bar{p} \to t\bar{t}) = 7.24^{+0.23}_{-0.27}$ pb for a top-quark mass of $m_t = 172.5$ GeV.[11] The second contribution to the production of top quarks takes place through EW processes that involve production of single top quarks. These final states have contributions from (i) the s-channel where a virtual W boson mediates the $q\bar{q}$ annihilation to produce a top and a b quark (tb), (ii) the t-channel, where a W boson is exchanged in the t-channel of an incident qg system, leaving a light quark, a top quark, and a possible accompanying b quark, in the final state (tqb), and (iii) the Wt-channel (Wt), where the final state consists of a W boson and a top quark that arise from an initial bg system, where the b quark corresponds to an intrinsic component of the proton (or antiproton) substructure ($b\bar{b}$ sea). Approximate NNNLO calculations for the sum of these three contributions predict a single top-quark production cross section of $\sigma(p\bar{p} \to tb/tqb/Wt) = 3.58 \pm 0.14$ pb, assuming a top-quark mass of $m_t = 172.5$ GeV.[12]

Within the SM, the top quark decays almost 100% of the time into a W boson and a b quark, and signatures for $t\bar{t}$ events can therefore be classified according to the decays of the W bosons. When both W bosons decay to $q'\bar{q}$ pairs, the final states of $t\bar{t}$ are referred as the alljets channel. It has a large branching ratio, but it is also contaminated by a large background from generic multijet production. The dilepton+jets channel ($\ell\ell$) corresponds to leptonic decays of both W bosons, either into $e\nu_e$ or $\mu\nu_\mu$ (with contributions from leptonic decays of the τ-lepton: $\tau_\ell \to \ell\nu_\ell\nu_\tau$). This channel has a small branching ratio, but also very little background contamination from, e. g., $\ell^+\ell^-$ Drell-Yan ($q\bar{q} \to \ell^+\ell^-$) or from WW, ZZ or WZ (diboson) production. The lepton+jets channel (ℓ+jets) consists of events where one W boson decays leptonically into $e\nu_e$ or $\mu\nu_\mu$ and the other W boson into $q'\bar{q}$. This $t\bar{t}$ final state has a large branching fraction, and a manageable background, mainly from W+jets and multijet production. Channels with a τ-lepton decaying to hadrons+ν_τ (τ_h) are treated separately, and have significant background from light jets misidentified as hadrons from τ decay. For some analyses, no explicit lepton-identification criteria are required to maintain sensitivity to all leptonic W-boson decays. However, in such cases, a large imbalance in transverse momentum ($\not\!\!E_T$), arising from undetected energetic neutrinos, is expected to be present in association with the jets. These criteria define the $\not\!\!E_T$+jets channel. CDF and D0 have measured the $t\bar{t}$ production cross sections in almost all of the above $t\bar{t}$ decay

modes. This provides the possibility of comparing measurements with predictions from the SM among the individual channels, and check thereby for any indication of physics beyond the SM.

Because of significant background, single top-quark production is studied only in final states where the W boson decays leptonically. The main backgrounds to EW single top-quark measurements arise from $t\bar{t}$, W+jets and multijet production.

The following sections present an overview of the top-quark measurements performed at the Tevatron. Section 3 provides results on the measurements of cross sections as well as their ratios in different channels. Properties of top quark are examined in Sec. 4. This starts with the measurements of m_t, followed by issues pertaining to helicities of the W bosons in $t \to Wb$ decays, angular production properties of t and $\bar{t}$ quarks, and, finally, measurements limited by statistical uncertainties that involve correlations in electric charges, in t and $\bar{t}$ spin and color flow in $t\bar{t}$ events, as well as issues pertaining to the width of the top quark and anomalous couplings examined through combined $t\bar{t}$ and single top-quark analyses. Section 5 describes searches for new phenomena in the top-quark sector, and a brief overall summary is given in Sec. 6.

3. Cross Sections for the Production of Top Quarks

First measurements of the $t\bar{t}$ production cross section were made at the Tevatron using the small data sample collected during Run I. The integrated luminosities in Run II were a factor of ≈ 100 larger, and led to improvements in techniques to separate signal from background, and thereby to a reduction in systematic uncertainties. As a result, measurements of the cross section improved rapidly in precision, reaching current uncertainties of $< 10\%$ that provide stringent checks of QCD predictions.[11,13,14,15] The next sections describe the present status of the cross-section measurements at the Tevatron, and outline the analyses techniques utilized in these measurements.

3.1. *From Discovery to Precision of Cross Sections*

While at the beginning of Run II, measurements of $t\bar{t}$ production cross sections had uncertainties of $\approx 30\%$,[16] nowadays, single measurements have reached precisions as small as 7%.[17] The most recent combination of CDF and D0 results for the total $t\bar{t}$ cross section, based on 8.8 fb^{-1} of data, is $\sigma(p\bar{p} \to t\bar{t}) = 7.65 \pm 0.42$ pb (for $m_t = 172.5$ GeV), corresponding to a precision of 5.5%.[18] Because BSM processes can affect differently each of the $t\bar{t}$ decay modes, measurements at the Tevatron experiments have sampled many final states. Event signatures are usually characterized by the presence of leptons and jets of large transverse momentum (p_T), and often of large $\not\!\!E_T$. Both collaborations have developed techniques that are best suited to exploit the strengths of each detector for the reconstruction and identification of such observables.[19,20,21]

Jets are reconstructed using different implementations of cone algorithms,[22] with possible requirements of having one or two jets that are candidates for arising from the evolution of bottom quarks. Such inference is based on methods of b-tagging that take advantage of the long lifetimes of hadrons that contain b quarks, as indicated by the presence of displaced ("secondary") vertices within jets that correspond to decays of b-quarks.[23] The use of b-tagging techniques has provided $t\bar{t}$ samples of sufficient purity to calculate a cross section just by counting events. Multivariate approaches have also been developed to distinguish jet flavors by combining properties of tracks and displaced vertices associated with jets.[24]

Another technique utilized for measuring the $t\bar{t}$ cross section consists of fitting a discriminant variable constructed from topological or kinematic information to distinguish signal from background processes.[17,25] This method makes no assumptions about the flavor of jets in $t\bar{t}$ events, but exploits differences in variables such as the magnitude of the sum of absolute p_T values of objects in an event (H_T), or relies on differences in event topologies that are expected for signal and background.

The development of multivariate techniques has played a particularly important role at the Tevatron in the search for single top-quark production. Although its cross section is about half that of the $t\bar{t}$ process, the background contribution from W+jets production is overwhelming. With only one top quark in the final state, the signature for single top-quark events is not as restrictive in reducing background as for $t\bar{t}$ production. To observe EW production of single top quarks requires therefore more inventive use of kinematic properties and b-tagging to define a discriminant that is sensitive to regions of phase space corresponding to large signal relative to background. Such regions of data can be fitted successfully to contributions from signal and background, in a procedure that takes into account uncertainties related to the normalization as well as the dependence on modeling of differential distributions in any given input variable. This method was applied by both CDF and D0 collaborations in their observation of a single top-quark signal,[8,9,10] and in the measurement of the cross section and the CKM matrix element $|V_{tb}|$.[26,27] Recent work has been extended to provide essentially model-independent results in the t-channel,[28] and to searches for new physics, to be discussed in Sec. 5.

3.2. *Current Status of cross sections*

The most precise measurements of cross sections are obtained using the ℓ+jets channels. CDF has complementary analyses, one based on counting events in samples with small background contributions, which is achieved by requiring the presence of two b-jets in each event, and, another, through a topological approach in the fitting of the output of an artificial neural network (NN) to events with more than two jets. In both types of measurements, the largest systematic uncertainty, which is due to the uncertainty on the integrated luminosity, can be reduced by normalizing to the observed inclusive yield of Z bosons in two-lepton final states, which can be calculated with great reliability.[17] Results based on 4.6 fb^{-1} of data are

combined using a best linear unbiased estimate (BLUE),[29,30] that yields a value of $\sigma(p\bar{p} \to t\bar{t}) = 7.32 \pm 0.52(\mathrm{stat}+\mathrm{syst})$ pb, assuming a mass of $m_t = 172.5$ GeV. The D0 collaboration finds a cross section of $\sigma(p\bar{p} \to t\bar{t}) = 7.78^{+0.77}_{-0.64}(\mathrm{stat}+\mathrm{syst})$ pb, by combining channels and using measurements that exploit both kinematic information and b-tagging information in 5.3 fb^{-1} of data.[25]

As mentioned before, although the $\ell\ell$ channel of $t\bar{t}$ production has a smaller branching fraction than the ℓ+jets mode, it has the advantage of a better signal to background ratio, even without use of b-tagging. These pure samples of $t\bar{t}$ events have also been explored by both collaborations. Using a sample of 5.4 fb^{-1}, D0 measures a cross section of $\sigma(p\bar{p} \to t\bar{t}) = 7.36^{+0.90}_{-0.79}(\mathrm{stat}+\mathrm{syst})$ pb for a top-quark mass of $m_t = 172.5$ GeV.[31] The cross section is extracted through a fit of the output of a NN b-tagging algorithm to data. At CDF, a counting experiment yields $\sigma(p\bar{p} \to t\bar{t}) = 7.66 \pm 0.46(\mathrm{stat}) \pm 0.66(\mathrm{syst}) \pm 0.47(\mathrm{lumi})$ pb for a data sample of 2.8 fb^{-1}.[32]

Identifying leptons, in particular electrons and muons, leads to drastically reduced backgrounds and therefore to simpler selection requirements for $t\bar{t}$ measurements. Nevertheless, the large sets of data, from well understood detectors, and the advances in analysis techniques have helped to produce excellent measurements even in the alljets channel. In this mode, final states are characterized by at least six jets, a signature that is similar to that of generic multijet production. To distinguish $t\bar{t}$ events from multijet background, b-tagging, kinematics and topological information is combined in a variety of ways. CDF utilizes the output of a likelihood fit exploited to measure m_t in a sample of events defined by a NN-based kinematic selection, together with the requirement of having at least 1 b-tagged jet, to extract a cross section of $\sigma(p\bar{p} \to t\bar{t}) = 7.2 \pm 0.5(\mathrm{stat}) \pm 1.1(\mathrm{syst}) \pm 0.4(\mathrm{lumi})$ pb for a top-quark mass of $m_t = 172.5$ GeV in 2.9 fb^{-1} of data.[33] D0 reduces the contamination from multijet events by requiring at least two b-tagged jets, and by implementing fits to the cross section based on a likelihood discriminant constructed from kinematic and topological information.[34] For a data sample of 1 fb^{-1}, D0 finds $\sigma(p\bar{p} \to t\bar{t}) = 6.9 \pm 1.3(\mathrm{stat}) \pm 1.4(\mathrm{syst}) \pm 0.4(\mathrm{lumi})$ pb, for $m_t = 175$ GeV.

These techniques have been extended to measurements in modes that have τ_h decays with signatures corresponding to the presence of large $\not\!\!E_T$ and at least four jets. To identify the τ_h decay products, which appear as narrow jets of hadrons, a set of neural networks is used by the D0 collaboration,[35,36] and a two-cones algorithm (a signal cone and an isolation annulus)[37] by CDF. The large background from multijet events is reduced through a restrictive cutoff on the output of a NN in the CDF analysis (that is also used to extract a value of m_t), as well as through differentiating background from signal in a fit of a distribution in NN output to the data, as done by D0. Both experiments apply their methodologies to samples with at least one b-tagged jet. Using 1 fb^{-1} of data, D0 measures a cross section of $\sigma(p\bar{p} \to t\bar{t}) = 6.9 \pm 1.2(\mathrm{stat})^{+0.8}_{-0.7}(\mathrm{syst}) \pm 0.4(\mathrm{lumi})$ pb for a top-quark mass of $m_t = 170$ GeV,[38] while in 2.2 fb^{-1} of data, CDF finds a cross

section of $\sigma(p\bar{p} \to t\bar{t}) = 8.8 \pm 3.3(\text{stat}) \pm 2.2(\text{syst})$ pb for a top-quark mass of $m_t = 172.5$ GeV.[39] CDF also measures the cross section in the $\not\!\!E_T$+jets channel, where no lepton identification is required, but by vetoing electrons and muons of large p_T to enhance the contribution from τ decays.[40] Event selection includes using a NN, and the cross section is measured by counting b-tagged jets. Background b-tag rates are obtained from three-jet data samples, which do not contain significant contributions from $t\bar{t}$ production. Utilizing 2.2 fb^{-1}, the measured cross section corresponds to $\sigma(p\bar{p} \to t\bar{t}) = 7.99 \pm 0.55(\text{stat}) \pm 0.76(\text{syst}) \pm 0.46(\text{lumi})$ pb for a top-quark mass of $m_t = 172.5$ GeV.

The measured $t\bar{t}$ cross section has become a precision standard at the Tevatron. Results have been found in agreement among channels, and each experiment has provided a combination of their most precise results, finding at CDF a value of $\sigma(p\bar{p} \to t\bar{t}) = 7.71 \pm 0.31(\text{stat}) \pm 0.40(\text{syst})$ pb, and at D0 a cross section of $\sigma(p\bar{p} \to t\bar{t}) = 7.56 \pm 0.20(\text{stat}) \pm 0.56(\text{syst})$ pb. These are the measurements entering the Tevatron combination[18] mentioned in the previous section, and are in excellent agreement with expectations from the SM.

Besides the production rate in different decay channels, another way to probe the presence of physics beyond the SM is by means of ratios of cross sections among different final states and the study of differential cross sections for a variety of variables. In particular, D0 has measured the ratios of cross sections for $\ell\ell$ channels relative to ℓ+jets channels ($R_\sigma^{ll/lj} = \sigma_{t\bar{t}}^{ll}/\sigma_{t\bar{t}}^{lj}$) and between the τl channel and the $\ell\ell$ and the ℓ+jets channels ($R_\sigma^{\tau l/ll-lj} = \sigma_{t\bar{t}}^{\tau l}/\sigma_{t\bar{t}}^{lj\&ll}$) in 1 fb^{-1} of data, by defining all modes to be mutually exclusive.[41] Results for $R_\sigma^{ll/lj} = 0.86^{+0.19}_{-0.17}$ and $R_\sigma^{\tau l/ll-lj} = 0.97^{+0.32}_{-0.29}$ are in agreement with the SM expectation of unity. The presence of contributions from BSM can be checked through the ratio of branching fractions $R_b = B(t \to Wb)/B(t \to Wq)$, where q represents any possible down-type quarks ($q = d, s, b$). This measurement is performed in the ℓ+jets and $\ell\ell$ channels by both CDF and D0 experiments, by fitting the number of events with 0, 1 and 2 b-tagged jets in the $t\bar{t}$ candidate samples. [42,43] In the most recent analysis by D0 , the procedure was extended to fit the b-tag NN output to data in $\ell\ell$ events, resulting in R_b to be $R_b = 0.90 \pm 0.04(\text{stat} + \text{syst})$ using 5.4 fb^{-1}of data.[44]. Results from both experiments were found consistent with the SM prediction of R close to unity.

To check predictions from perturbative QCD, and to define some generic tests of the presence of physics BSM, CDF and D0 study differential cross sections for a variety of variables in $t\bar{t}$ events. While CDF examines the $t\bar{t}$ invariant mass ($m_{t\bar{t}}$) in 2.7 fb^{-1},[45] D0 considers the p_T of the top quarks in 1 fb^{-1} of data.[46] For both studies, events must have at least one b-tagged jet in the ℓ+jets final state, which provides reconstruction of the $t\bar{t}$ final state with good resolution. Both the p_T and $m_{t\bar{t}}$ distributions are unfolded to the parton level, thereby correcting the data for effects of resolution, and acceptance. D0 compares the p_T distribution expectations from several MC generators, while CDF calculates the consistency of

the $m_{t\bar{t}}$ distribution with expectations of the SM.

Although the main production mode for top quarks at the Tevatron is the $p\bar{p} \to t\bar{t}$ reaction, the rate for EW production of single top quarks is about half that of $t\bar{t}$, but as mentioned previously, with a much smaller signal-to-background ratio. Observation of single top quarks was announced by CDF and D0 in 2009.[8,9,10] This milestone was achieved largely through the development of multivariate techniques that exploit the small differences in kinematic properties between single top quark production and background processes. Many analyses have been performed using a variety of methods, such as artificial neural networks,[47] Bayesian NN (BNN) discriminant,[48] discriminants based on matrix elements (ME)[49], boosted decision trees (BDT)[50,51] and multivariate likelihood functions.[52] These analyses are based on selections that require events containing a lepton (electron or muon) of high p_T, significant $\not\!\!E_T$ and two or more jets, one of which is b-tagged. The sensitivity of the analyses is improved by separating events into different jet multiplicities, as well as according to the number of b-tagged jets in an event. Since the measurements are only partly correlated, final results are obtained by combining the output of each analysis into a single discriminator. D0 uses a set of BNN discriminators, while CDF relies on the "NEAT"[53] NN, which is later combined with the output of an orthogonal analysis that selects events requiring just jets and large $\not\!\!E_T$. Using 2.3 fb^{-1} of integrated luminosity, D0 finds a cross section for the combined s and t channels of $\sigma_{s+t} = 3.94 \pm 0.88$ pb (for $m_t = 170$ GeV),[10] and CDF, using a sample of 3.4 fb^{-1}, measures $\sigma_{s+t} = 2.3^{+0.6}_{-0.5}$ pb (for $m_t = 175$ GeV).[8,9] Measurements from both collaborations are combined in a Bayesian analysis, yielding a cross section of $\sigma_{s+t} = 2.76^{+0.56}_{-0.47}$ pb (for a $m_t = 170$ GeV).[54] Since this cross section is proportional to $|V_{tb}|^2$, without assuming unitarity of the 3x3 CKM matrix (but assuming the dominance of $t \to Wb$ decays), a value of the matrix element $|V_{tb}| = 0.88 \pm 0.07$ is extracted for the combined result, with a lower limit at 95% confidence (CL) of $|V_{tb}| > 0.77$.

A new measurement from D0, using 5.4 fb^{-1} of data, finds a cross section for $\sigma(p\bar{p} \to tqb + X)$ of 2.90 ± 0.59 pb (for $m_t = 172.5$ GeV) for inclusive t-channel production, without any assumption on the production rate for the s-channel.[28] The values of $\sigma(p\bar{p} \to tb + X) = 0.68^{+0.38}_{-0.35}$ pb and $\sigma(p\bar{p} \to tqb + X) = 2.86^{+0.69}_{-0.63}$ pb, are found when the SM tqb and tb production rates are assumed, respectively in these two analyses.

Large data samples have also been used to pursue direct searches for single top-quark production in channels such as τ+jets at the Tevatron. While the $\not\!\!E_T$ + jets mode is sensitive to $W \to \tau\nu_\tau$ decays, another possiblity to study events with sensitivity to $W \to \tau\nu_\tau$ is by measuring events with τ_h decays. The latest study from D0 has focused on the contribution from τ_h decays in 4.8 fb^{-1} of data.[55] Using a BDT discriminator to identify τ_h decays, as well as to separate single top-quark events from background, the measurement yielded an upper limit on the single top quark cross section of 7.3 pb at a 95% CL. Adding this channel to the D0 observation analysis provides an increase of signal acceptance of $\approx 30\%$ and a gain of 4% in

expected sensitivity.

4. Properties of the Top Quark

Measuring the properties of top quarks is essential for gauging to what extend they coincide with the predictions of the SM. Many innovative techniques have been developed to measure these properties, and will be described briefly in the sections below, starting with the measurement of m_t. Some of the precision results require large data samples, and combining of results from several sources, which we also discuss below.

4.1. *Measuring the Mass of the Top Quark*

An important property of the top quark is its mass. The value of m_t is a free parameter of the SM, which together with the mass of the W boson (M_W) constrains the mass (m_H) of the Higgs boson (H) through EW quantum corrections. Comparing this indirect prediction with a direct measurement of m_H provides a stringent test of the consistency of the SM.

Prior to the data from Run II, the value of m_t was known only to an uncertainty of the order of 5 GeV.[49] Even with the $\approx$ 100-fold increase anticipated in luminosity from Run II, it was not expected that the precision on m_t would improve greatly because of limitations from systematic uncertainties. Nevertheless, the best single analyses have achieved precisions of 1.3 GeV while a combination of the best Tevatron results has an uncertainty of 0.94 GeV, corresponding to an accuracy of 0.54 %.[3] This makes the mass of the top quark the best known mass in the quark sector of the SM. This achievement was realized largely through the introduction of the so called "*in-situ*" jet calibration (see below),[56] and through innovations in analyses, such as the matrix element (ME) approach, first used successfully in Ref.[49]. Both developments will be described below, as well as other methods of analysis pioneered at the Tevatron for measuring m_t.

Although the mass of the top quark is reflected in the kinematic distributions of all of its decay products, there are primarily three main methods that have evolved for measuring m_t. These are: (i) the template method, (ii) the ME method, and (iii) the ideogram method. All these rely on the calibration of the measured m_t through Monte Carlo (MC) pseudo-experiments, the analyses of which is used to correct for simplifications or other assumptions of each method. Each pseudo-experiment contains a mixture of $t\bar{t}$ signal (simulated using MC generators) and background events (either from MC or based on other data) that reflects the composition of the analysis samples in data. The relation between the mean value of m_t extracted in the pseudo-experiment and the input is usually fitted to a linear dependence, and used to correct the value of m_t found for data. Pseudo-experiments are also used to calibrate the statistical uncertainty of a given method. For ℓ+jets or alljets channels, where at least one of the W bosons from the top quarks decays into two light quarks, the jets from the W boson can be used to recalibrate the jet energy

scale (JES) through an *in-situ* jet calibration. For true $t\bar{t}$ events, the invariant mass of the two jets from the W boson can be constrained to the world average value of M_W,[57] and the result used to adjust the energy scale of all jets (JES). This procedure reduces the impact of the uncertainty on the absolute jet energy in the measurement of m_t.

The simplest method for measuring m_t is the template method, which relies on comparing the properties of an observable whose value is correlated with the mass of the top quark, which we wish to extract from the data. It is based on MC distributions (templates) in this observable, generated for different values of m_t. The observable found to be most strongly correlated with m_t is, not surprisingly, the invariant mass of the top quark reconstructed from its decay products. This reconstruction can be performed using a kinematic fit to the candidate events, assuming the constraints of the $t\bar{t}$ hypothesis. To improve the statistical power of the analysis, all or the most likely solutions to the jet permutations in the $t\bar{t}$ hypotheses are considered in the analysis. Often, just the reconstructed m_t with the best and second-best value of χ^2 fit probability are retained. Observables other than the reconstructed m_t can also be exploited to minimize sensitivity to some specific uncertainty, such as the uncertainty from jet energy corrections. The latter was done by CDF through the use of the observed decay lengths of B hadrons evolved from b quarks. This is usually implemented in the plane transverse to the incident proton and antiproton beams.[58] Alternatively, variables such as the transverse momenta of leptons from decays of W bosons can be used in these studies.[59] The sensitivity of the template method is not as high as that of other methods that rely on more kinematic information in an event, or that assign larger weight to more well-measured and more likely $t\bar{t}$ events. However, with the large data samples available at the end of Run II and smaller impact of statistical uncertainties, this method is now very competitive. The simpler template method has therefore been used to measure m_t in most $t\bar{t}$ decay channels, as summarized in what follows.

With 5.6 fb^{-1} of data, CDF performs a simultaneous fit to the ℓ+jets and $\ell\ell$ channels, using *in-situ* jet calibration for events with one or two b-tagged jets in ℓ+jets events, and for $\ell\ell$ data that contain either untagged or b-tagged jets.[60] Three observables are used to characterize the ℓ+jets channel: the reconstructed invariant mass of the top quark for the two jet-permutations with the best and next-best fit-χ^2 to the $t\bar{t}$ hypothesis, and the mass of the two untagged jets that provides an invariant mass (m_{jj}) closest to the world average value of M_W. Two observables are used for the $\ell\ell$ channel: (i) the reconstructed m_t based on the "neutrino weighting" algorithm (described below), and (ii) the variable m_{T2}, which is related to the transverse mass of the decay remnants of the top-quark candidates.[61] Two or three-dimensional templates for signal and background are constructed from MC samples using kernel-density estimators.[62] The requisite distributions, generated at discrete input values of m_t, are smoothed and interpolated using the local polynomial-smoothing method of Ref.[63]. The resulting m_t is 172.2$\pm$1.2(stat)$\pm$0.9(syst) GeV in the ℓ+jets channel,

and $m_t = 170.3 \pm 2.0(\text{stat}) \pm 3.1(\text{syst})$ GeV in the $\ell\ell$ channel.[60] The same technique is exploited in an NN-based selection of $\not\!\!E_T$+jets events that relies on the two reconstructed invariant masses of the top quark and m_{jj}. This yields: $m_t = 172.3 \pm 2.4(\text{stat}) \pm 1.0(\text{syst})$ GeV in 5.7 fb^{-1} of data.[64]

CDF also uses the template method to measure m_t in the alljets channel in 5.8 fb^{-1} of data.[65] Templates are formed for the mass reconstructed from the b-light-jet system and the m_{jj} that correspond to the best fit to a $t\bar{t}$ hypothesis, following a NN-based selection. The measured top-quark mass is $m_t = 172.5 \pm 1.4(\text{stat}) \pm 1.5(\text{syst})$ GeV.

D0 also uses a template method for the dilepton analysis in 5.3 fb^{-1} of data, to measure the top-quark mass based on a neutrino weighting method[66] that integrates over the rapidities assumed for the two neutrinos, using the kinematic constraints of the $t\bar{t}$ hypothesis that depend on m_t. Weights are assigned to each choice of rapidities by comparing the resulting solutions for the summed $|\vec{p}_{T1} + \vec{p}_{T2}|$ of the two neutrinos to the measured value of $\not\!\!E_T$. The mean and RMS values of the distributions in event weights are used as observables to extract the most probable mass of the top quark. In this dilepton analysis, the dominant systematic uncertainties (from jet energy calibration) are reduced using a correction obtained from $t\bar{t} \to \ell$+jets events. D0 obtains $m_t = 174.0 \pm 2.4(\text{stat}) \pm 1.4(\text{syst})$ GeV.[66]

The ME method is based on using all measured kinematic quantities to construct a probability for each event that relies on a leading-order matrix element, and that integrates over the unmeasured quantities. This method offers maximal statistical sensitivity to m_t, as it uses all the available kinematic information to weight events according to their degree of agreement with background or signal hypotheses. It is however a rather CPU intensive formulation. This powerful technique was developed to measure the top-quark mass, and was adapted subsequently to measure the W helicity in top-quark decays and to use as a discriminant in measuring the single top-quark cross section, $t\bar{t}$ spin correlations, as well as to search for the Higgs boson at the Tevatron. The event probability is constructed from signal and background probabilities, weighted by their fraction of contributions. The probability for signal is found by convoluting the parton-level differential cross section for $q\bar{q} \to t\bar{t}$ with parton distribution functions (PDF) and resolution functions that take account of detector resolution as well as parton evolution. These transfer functions $W(x, y)$ correspond to the probability of observing a given measured quantity x that corresponds to a parton level quantity y. When the analysis uses *in-situ* jet calibration, the jet transfer functions can be expressed in terms of an overall jet energy scale factor that is determined simultaneously with m_t. The background probability is also defined in the analysis through an appropriate matrix element. The likelihood function for a given event sample is obtained from the product of the individual event probabilities.

CDF and D0 have used the ME technique in analyses of ℓ+jets and $\ell\ell$ channels. CDF considers the $gg \to t\bar{t}$ matrix element in addition to the $q\bar{q} \to t\bar{t}$

process, and takes account of both momentum and angular resolutions of jets in the transfer functions. Signal is discriminated from background through a NN. Using a quasi-MC technique, the ME is integrated over the dimensions representing the kinematics of the final state. In 5.6 fb^{-1} of data, CDF measures $m_t = 173.0 \pm 0.7(\text{stat}) \pm 1.1(\text{syst})$ GeV.[67] For the signal probability, the D0 analysis relies only on the $q\bar{q} \to t\bar{t}$ matrix element, and the W+4 partons process for describing the background from W+jets and multijet events. The result is $m_t = 174.9 \pm 0.8(\text{stat}) \pm 1.2(\text{syst})$ GeV for 3.6 fb^{-1} of data.[68] In the $\ell\ell$ channel, CDF uses event selections based on NN training using neuroevolution.[69] Background probabilities are contructed with matrix elements for the Z/γ^*+jets and W+jets matrix processes. Using 2 fb^{-1} of data, CDF obtains $m_t = 171.2 \pm 2.7(\text{stat}) \pm 2.9(\text{syst})$ GeV.[70] D0 uses Z+2 jets matrix elements for the background probabilities in their $\ell\ell$ analysis.[71] An additional transfer function is used to describe the energy of the final state lepton for the $Z \to \tau^+\tau^-$ background in the $e\mu$ channel. In 5.4 fb^{-1} of data, D0 finds $m_t = 174.0 \pm 1.8(\text{stat}) \pm 2.4(\text{syst})$ GeV.

The third general way of extracting m_t is referred to as the ideogram method, and can be thought of as an approximation to the ME approach. The procedure defines a probability for observing the reconstructed m_t in an event that is based on the mass resolution and an assumed input value of m_t. Specifically, the probability for signal is obtained through a convolution of a Gaussian for the mass resolution with a Breit-Wigner characterizing the decay of top quarks, while the background probability is taken from MC simulation. D0 has performed a measurement using this technique in the ℓ+jets channel by factorizing the probabilities for signal and background. With *in-situ* jet calibration, in 0.43 fb^{-1} of data, D0 obtains $m_t = 173.7 \pm 4.4(\text{stat} + \text{JES})^{+2.1}_{-2.0}(\text{syst})$ GeV.[72] CDF measures m_t in the alljets channel using the same technique in 0.31 fb^{-1} of data, and finds $m_t = 177.1 \pm 4.9(\text{stat}) \pm 4.7(\text{syst})$ GeV.[73]

The above measurements in the ℓ+jets and alljets channels are limited by systematic uncertainties. For the full Tevatron data, this is also expected to be the case even for the $\not\!\!E_T$+jets channel. The largest systematic uncertainties in the ℓ+jets analyses arise from the residual uncertainty on JES and from modeling of signal, for the alljets channel it is the modeling of signal and background and the $\ell\ell$ channel is limited by the uncertainty on JES. However, as the statistical uncertainty decreases, the uncertainty from *in-situ* jet calibration also decreases with more data.

Different measurements of m_t at the Tevatron can also be combined to improve the overall uncertainty on m_t. And in fact, eight measurements from CDF and four from D0 have been combined using the BLUE method to account for the systematic uncertainties of the input measurements and their correlations. This yields a value of $m_t = 173.18 \pm 0.56(\text{stat}) \pm 0.75(\text{syst})$ GeV, which has a precision of 0.54%.[3] The combination has a χ^2 of 8.3 for 11 degrees of freedom, corresponding to a 69% probability for agreement among the twelve input values. The CDF and D0 ℓ+jets measurements carry the largest weights in the combination, which is followed by the CDF measurement in the alljets final state.

All the measurements presented so far rely on the reconstructed decay products of the top-quarks and assume that the measured top-quark mass is close to the "pole" mass. However, for a colored particle such as a top quark, this definition is intrinsically ambiguous by a value of the order of $\Lambda_{\rm QCD}$.[74,75,76] Apart from this theoretical ambiguity, additional questions of interpretation arise, as the experimental measurements are calibrated using MC generators that include models for parton evolution ("showering") and hadronization. These processes also introduce an ambiguity of the order of $\Lambda_{\rm QCD}$ in interpreting m_t as the pole mass.[77] An alternative method, mostly free of these ambiguities is based on extracting m_t by comparing the observed $t\bar{t}$ cross section with theoretical predictions. Determining the mass from the cross section is less precise than using the direct methods described above, but it provides m_t in a well-defined renormalization scheme. D0 has performed such an extraction using the measured $t\bar{t}$ cross section in 5.3 fb^{-1} of ℓ+jets data, for different assumptions of m_t.[78] The top-quark mass is extracted as the most probable value of a normalized joint-likelihood function formed from the theoretical prediction with the measured cross section, taking account of the uncertainties from choices of PDF, renormalization and factorization scales, and other experimental uncertainties. Using the NLO+NNLL calculation of Refs.[79,80], D0 measures the pole mass to be $m_t = 167.5^{+5.4}_{-4.9}$ GeV. This method is also used to extract the mass in the $\overline{MS}$ renormalization scheme.[78]

Because the top quark decays before hadronizing, $t\bar{t}$ events provide a unique opportunity to study the properties of an essentially bare quark. Both template and matrix-element methods have been extended to check the CPT theorem, namely the conservation under the product of the charge conjugation (C), parity conjugation (P) and time reversal (T) operation in the top-quark sector. Tests have been performed by measuring the $t-\bar{t}$ mass difference. CDF uses the template method in the ℓ+jets channel with 8.7 fb^{-1} to get $m_t - m_{\bar{t}} = -1.95 \pm 1.11(\text{stat}) \pm 0.59(\text{syst})$ GeV.[81] D0 measures the mass difference using the matrix-element method in the ℓ+jets channel with 3.6 fb^{-1} of data $m_t - m_{\bar{t}} = 0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV.[82] Both results agree within less than 2 standard deviations with the CPT-conserving hypothesis of no mass difference.

4.2. *Other Properties*

With the aim of revealing whether the massive quark observed is indeed the top quark postulated by the SM, other properties besides its mass are analyzed at the Tevatron. One of the first of such measurements was the study of the helicity of the W boson produced in the $t \to Wb$ decay. In the SM right-handed W^+ bosons are strongly suppressed by the V-A structure of the EW interaction. In particular, for $m_t = 172.5$ GeV, the W^+ helicity is expected to have a longitudinal component of $f^0 = 0.696$ and a left-handed component of $f^- = 0.303$. These helicity fractions obtained from a first-order in perturbative expansion,[83] can be affected through higher-order EW effects or uncertainties on m_t, m_W or m_b by 1-2 %.[84,85,86] Sig-

nificant deviations from these predictions can indicate therefore the presence of new physics. First results on the observed helicities were obtained in the ℓ+jets channel through studies of distributions of the helicity angle ($cos\theta^*$) which is the angle of the down-type fermion (charged lepton) in the rest frame of the W boson relative to the direction of the top quark direction in the $t\bar{t}$ rest frame. This was done by comparing data with templates extracted from MC simulations that were generated with different values of f^+ for the fixed (expected) value of f^0. These results were rapidly improved by the addition of the dilepton mode, and the use of results from the $W \to q'\overline{q}$ decays. For the latter, the down-type quark jet is chosen at random in the calculation of $cos\theta^*$, as this inclusion adds sensitivity to the measurement. More recent analyses include model-independent fits to simultaneous measurements of f^0 and f^+. Performing a joint binned-likelihood fit to 5.4 fb^{-1} in the ℓ+jets and $\ell\ell$ decay modes, D0 finds $f^0 = 0.669 \pm 0.078(\text{stat}) \pm 0.065(\text{syst})$ and $f^+ = 0.023 \pm 0.041(\text{stat}) \pm 0.034(\text{syst})$ for a model-independent fit, and, respectively, $f^+ = 0.010 \pm 0.022(\text{stat}) \pm 0.030(\text{syst})$ and $f^0 = 0.708 \pm 0.44(\text{stat}) \pm 0.048(\text{syst})$ for fits with f^0 or f^+ fixed to their SM values respectively.[87] CDF performs this measurement using 2.7 fb^{-1} of data in the ℓ+jets channel, that introduces a likelihood technique based on a matrix elements for $t\bar{t}$ production as well as for the main background process from W+jets production.[88] This technique was developed for the top-quark mass measurement, and utilized instead an expression for the ME in terms of the W boson helicity fractions and $cos\theta^*$. The study was recently updated using all the data, determining simultaneously $f^0 = 0.726 \pm 0.066(\text{stat}) \pm 0.067(\text{syst})$ and $f^+ = -0.045 \pm 0.044(\text{stat}) \pm 0.058(\text{syst})$.[89] For the dilepton channel, the measurements are performed using a fit of the two-dimensional space of the measured $cos\theta^*$ in a sample of 5.1 fb^{-1}.[90] Combining this with the above 2.7 fb^{-1} ℓ+jets result yields $f^0 = 0.84 \pm 0.09(\text{stat}) \pm 0.05(\text{syst})$ and $f^+ = -0.16 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$ for the simultaneous measurements and $f^+ = -0.07 \pm 0.02(\text{stat}) \pm 0.04(\text{syst})$ and $f^0 = 0.64 \pm 0.06(\text{stat}) \pm 0.05(\text{syst})$ when f^0 or f^+ are fixed, respectively, to their SM expectations. Results from both experiments are combined to yield $f^0 = 0.722 \pm 0.081(\text{stat} + \text{syst})$ and $f^+ = -0.033 \pm 0.046(\text{stat} + \text{syst})$ and when fixing one of the helicity fractions to the SM prediction the results are $f^0 = 0.682 \pm 0.057(\text{stat} + \text{syst})$ and $f^+ = -0.015 \pm 0.035(\text{stat} + \text{syst})$.[91] These measurements are consistent with the SM with no indication of the presence of contributions from new phenomena.

Studies have also been related to properties of the $t\bar{t}$ production process. A measurement of the fraction of gg fusion process (f_{gg}) in the $t\bar{t}$ production performed at CDF exploited the difference in kinematic characteristics of gg and $q\bar{q}$ contributions to distinguish the two mechanisms. Eight variables, describing production and decay properties, all sensitive to the production mechanism, are fed into a NN for two b-tagged event categories: 1 and > 1 b-tagged jets. The outputs of the NN are formed into templates to represent background, $q\bar{q}$, and gg events that are used in a likelihood function that is maximized to find the estimator for f_{gg}. Using the Feldman-Cousins prescription,[92] measured values are mapped to a range of MC-

generated true fractions. For the ℓ+jets channel, in a sample of 1 fb^{-1} of data CDF finds $f_{gg} < 0.33$ at a 68% CL.[93] This result is combined with another measurement that relies on the higher probability for a primary gluon, than for a quark, to radiate a low energy gluon in the production process, obtaining a value of $f_{gg} = 0.07^{+0.15}_{-0.07}$, in agreement with the SM prediction.[93]

While at leading order, QCD predicts that angular distributions of t and $\bar{t}$ production should be forward-backward symmetric at the Tevatron, a positive asymmetry (more t and $\bar{t}$ produced along the incident p and $\bar{p}$), A_{FB}, is expected at higher orders.[94,95,96] Negative contributions to A_{FB} arise from the interference of diagrams with initial and final state radiation, while positive terms arise from interference of the Born and box diagrams in two body $t\bar{t}$ production. D0 explores A_{FB} defined in terms of the rapidity difference (Δy) between the top and antitop quarks in ℓ+jets events in a sample of 5.4 fb^{-1}. After correcting for acceptance and detector resolution through an unfolding method with fine binning and explicit regularization, D0 finds $A_{FB} = (19.6 \pm 6.5)\%$,[97] to be compared with the prediction from the Monte Carlo generator MC@NLO of $(5.0 \pm 0.1)\%$.[98] An alternative approach is also performed by calculating the asymmetry based on the rapidity of the lepton. This result, which does not depend on the full reconstruction of the $t\bar{t}$ system, yields $A^{l}_{FB} = (15.2 \pm 4.0)\%$[97] which is predicted to be $A^{l}_{FB} = (2.1 \pm 0.1)\%$.[98] These values disagree with expectations by up to 3 standard deviations. However, no statistically significant dependence of A_{FB} is observed on the invariant mass of the $t\bar{t}$ system ($m_{t\bar{t}}$) or on $|\Delta y|$. CDF, using an integrated luminosity of 9.4 fb^{-1} to perform an inclusive measurement of A_{FB}, and to examine the dependence on kinematic properties in the ℓ+jets channels, corrects the reconstructed A_{FB} for acceptance and resolution of the detector by using a regularized algorithm, to unfold the resolution, which is based on Singular Value Decomposition,[99,100] and bin-by-bin correction for acceptance obtained from the Monte Carlo generator POWHEG.[101] The inclusive result is $A_{FB} = (16.4 \pm 4.5)\%$,[102] which exceeds the NLO prediction from POWHEG by 2 standard deviations (including a 30% uncertainty on the prediction,[103] and EW corrections that amount to a factor of $\approx 26\%$) [104,105,106]. A linear fit is carried out as a function of $m_{t\bar{t}}$, finding a slope of $(15.2 \pm 5.0) \times 10^{-4}$ GeV^{-1}, which exceeds by 2.3 standard deviations the NLO prediction of $(3.4 \pm 1.2) \times 10^{-4}$ GeV^{-1}. A fit to $|\Delta y|$ yields a slope of $(28.6 \pm 8.5) \times 10^{-2}$, which is 2.1 standard deviations away from the expectation of $(10.0 \pm 2.3) \times 10^{-2}$. The significance of the observed difference between data and theory for reconstructed $t\bar{t}$ events, after background subtraction, is reflected by the p-values for the slopes to have fluctuated to values as large as observed in data. These probabilities are 14.7×10^{-3} for $|\Delta y|$ and 7.4×10^{-3} for $m_{t\bar{t}}$, corresponding to 2.2 standard deviations and 2.4 standard deviations, respectively. These results have stimulated many new theoretical work, not only in the SM context but also new physics models that would explain the observed asymmetry and that should accommodate the consistency with the SM of the measured cross section and $m_{t\bar{t}}$ spectrum.[107] In addition,

many cross-checks were performed on these results by both CDF and D0, including a check of the asymmetry as function of the transverse momentum of the $t\bar{t}$ system. Such measurements contribute to the on-going studies needed to establish the origin of these discrepancies. In fact both collaborations are also exploring the issue of the asymmetry in other final states, such as the dilepton channel. In this mode, D0 measures angular asymmetries based on η distributions of charged leptons. The resulting A^l_{FB} is $5.8 \pm 5.1(\text{stat}) \pm 1.3(\text{syst})\%$,[108] which, including QCD and EW corrections, is in agreement with the MC@NLO prediction of $(4.7 \pm 0.1)\%$.[109]

4.3. *Properties Made Accessible through Large Statistics*

While the data sample of Run I was too small to study all aspects of the properties of top quarks, the large amount of data collected by now opens up the possibility of studying more subtle properties. In particular, the charge of the top quark, and $t\bar{t}$ spin correlations have now turned into precision measurement, while effects of color flow from the presence of W bosons in $t\bar{t}$ events (but not in background) and $t\bar{t}$ production associated with a photon were only recently considered for study.

While the charge of the top quark in the SM is predicted to be $+2/3$ of the electron charge, an exotic charge of $-4/3$ could also be possible.[110] CDF and D0 both perform measurements of the charge of the top quark. The measurements are performed in the ℓ+jets final state, in events with at least one b-tagged jet. A kinematic fit is performed to assign the final state t and $\bar{t}$ decay products to their proper top and antitop quark; where constraints from m_W and m_t are applied in the analysis. The measurements of charge rely on the observed charge of the lepton from $W \to l\nu$ decay, combined with the charge of the b-jet from the same or the other top quark. D0 performed the first measurement of the charge of the top quark using 0.37 fb^{-1} of data, where a jet charge algorithm was applied to extract the charge of the b-jet.[111] In this method, a weighted sum of the charges of the tracks is calculated within the jet and calibrated using an orthogonal data sample enriched in $b\bar{b}$ events, where one of the b-jets is also tagged through the presence of a soft (low-p_T) muon. This calibration is used to analyzed the $t\bar{t}$ sample, providing templates representing SM and exotic choices to model the charge of top quarks. The result of a fit to data excludes in the exotic hypothesis at a 92% CL.

CDF exploits an alternative approach, requiring at least one jet to be b-tagged through a displaced vertex, and at least one (which can be the same jet) to contain a soft lepton from semileptonic B decay. Using 2.7 fb^{-1} of data, CDF excludes the exotic model at a 95% CL.[112]

Another way to access the charge of the top quark is to study directly the electromagnetic coupling strength in top-quark electromagnetic interactions through photon radiation in $t\bar{t}$ events. The $t\bar{t}\gamma$ coupling parameters are also sensitive to new physics models.[113] CDF performed a measurement of the cross section for $t\bar{t}\gamma$ production together with the inclusive production of $t\bar{t}$ events using a selection optimized for the $t\bar{t}\gamma$ candidates in the ℓ+jets and $\ell\ell$ samples and requiring at least

one jet to be identified as coming from a b quark. The $t\bar{t}\gamma$ sample requires the photon to have $E_T > 10$ GeV and to be in the central region of the detector. In the $t\bar{t}\gamma$ signature, the background is dominated by events in which an electron is misidentified as a photon. Using data corresponding to 6 fb^{-1}, 30 $t\bar{t}\gamma$ candidates are observed compatible with the predictions from the SM. The $t\bar{t}\gamma$ cross section yields 0.18 ± 0.08 pb and the ratio of production of $t\bar{t}\gamma$ to $t\bar{t}$ is 0.024 ± 0.009. This corresponds to the first experimental evidence for $t\bar{t}\gamma$ production.[114]

Another analysis that gained sensitivity with collected data is the study of $t\bar{t}$ spin correlations. Despite that the top quark is expected to be produced unpolarized at lowest order in the SM, the spin of the t and $\bar{t}$ quarks are predicted to be correlated. The short lifetime of the top quark assures that the information about its spin is preserved in its decay products, which can be used to measure the spin correlations of t and $\bar{t}$. While previous data samples were not sufficiently sensitive to provide definitive results on spin correlations, several studies performed more recently at CDF and D0 in the dilepton and the ℓ+jets channels have been more conclusive.

CDF and D0 use template-based methods that rely on the fact that the double differential cross section, $1/\sigma \times d^2\sigma/(d\cos\theta_1 d\cos\theta_2)$, can be written as $1/4 \times (1 - C\cos\theta_1\cos\theta_2)$, where C is the spin correlation strength, and θ_1 and θ_2 are respectively, the angle of the down-type fermions from $t \to W^+b$ and $\bar{t} \to W^-b$ decays of the W^+ and W^- bosons in the t or $\bar{t}$ quark rest frame relative to some chosen quantization axis. The SM prediction for the spin correlation strength (C) depends on the collision energy ($\sqrt{s}$) and the choice of quantization axis, and at NLO corresponds to $C = 0.78$ for $\sqrt{s} = 1.96$TeV, as defined relative to the beam direction.[115] The optimal choice for final-state particles is the charged lepton and the down-type quark from the W-boson decay, both with spin-analyzing power of unity. Because of the experimental challenge of distinguishing up-type from down-type quarks, the dilepton channel has greatest sensitivity to spin correlations. The D0 experiment extracts C by forming templates for $C = 0$ and for the values of C expected for the coefficient of $\cos\theta_1\cos\theta_2$ in the SM, and fitting these two possibilities in an analysis of 5.4 fb^{-1} of data. In the beam basis, C is found to be $C = 0.10 \pm 0.45(\mathrm{stat} + \mathrm{syst})$, in agreement with the prediction of the SM.[116] The first measurement of C by CDF is in the ℓ+jets channel, where templates of same and opposite $t\bar{t}$ helicity are fitted to the data. Using 4.3 fb^{-1} of data, CDF measures $C = 0.72 \pm 0.64(\mathrm{stat}) \pm 0.26(\mathrm{syst})$ in the beam basis.[117]

In addition to the template based method, D0 explores a technique based on calculating matrix elements that consider spin correlations (labeled as $H = c$) and matrix elements with uncorrelated spins ($H = u$). From these matrix elements, a discriminant R can be constructed as $R = P_{sig}(H = c)/[P_{sig}(H = c) + P_{sig}(H = u)]$.[118] Using the same data sample of 5.4 fb^{-1} as used in the template-based analysis in dilepton events, the method provides a 30% improvement in sensitivity, yielding $C = 0.57 \pm 0.31(\mathrm{stat} + \mathrm{syst})$.[119] Applying the ME-based method to 5.3 fb^{-1} of ℓ+jets events, and combining the result with the measurement in the dilepton

final state, yields first evidence for a non-vanishing $t\bar{t}$ spin correlation.[120]

D0 performed the first study of color flow in $t\bar{t}$ events. Since color charge is a conserved quantity in QCD, two final-state particles on the same line of color flow are termed to be color-connected to each other. Using 5.3 fb^{-1} of ℓ+jets events, D0 exploits a tool called jet pull,[121] which is based on the measurement pattern of jet energy distributed in the η-ϕ plane, and measures the color flow between a pair of jets, in an attempt to distinguish color-octet from color-singlet states. For a color-singlet state, the pulls of both jets tend towards each other, in contrast to a jet pair from a color-octet state, where the pulls point in opposite directions along the beam axis. The known environment of ℓ+jets $t\bar{t}$ events provides a testing ground for this tool, before it can also be applied to searches for BSM contributions. The two light jets from the decay of the W boson are expected to originate from a color singlet. By introducing a hypothetical "W" boson that decays as color octet, and comparing templates of jet pull for octet and singlet components to data, the fraction of color-singlet decays is found to be $f = 0.56 \pm 0.38(\mathrm{stat} + \mathrm{syst}) \pm 0.19(\mathrm{MCstat})$, with an expected exclusion of a color-octet "W" boson at the 99% CL.[122]

4.4. *Properties extracted from multiple inputs*

Certain top-quark properties, or searches for new physics in the top-quark sector, can be elucidated by combining two a priori independent measurements that can yield additional information on the parameters of the top quark.

An example of a combination of different measured parameters that yields a new result is the determination of the width of the top quark (Γ_t). In the SM, Γ_t can be computed from the value of m_t. For $m_t = 172.5$ GeV, the expectation is $\Gamma_t = 1.33$ GeV. The value of Γ_t can be affected by the presence of new physics. With 4.3 fb^{-1} of data, CDF extracts Γ_t in the ℓ+jets channel directly using a standard template method based on the distribution of the reconstructed m_t values, with Γ_t as the parameter of interest. An upper limit of $\Gamma_t < 7.6$ GeV is established at 95% confidence by applying a Feldman-Cousins approach.[123] The resolution of the reconstructed top-quark mass is limited especially by the resolution in JES and by the uncertainty on modeling the m_t resonant spectrum. Hence, since the predicted Γ_t is far smaller than the mass resolution of the reconstructed top quark, it is very difficult to measure Γ_t directly. To overcome this, D0 extracts Γ_t from its partial width $\Gamma(t \to Wb)$, which is determined from the t-channel of the single top-quark production cross section.[124] This coupled with the top-quark branching fraction $\mathcal{B}(t \to Wb)$ measured using the ratio $R = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$[125], and the assumption that $\Gamma_t = \Gamma(t \to Wb)/\mathcal{B}(t \to Wb)$, (namely that $\mathcal{B}(t \to Wq) = 1$) and that the Wtb coupling is the same in the production and decay of the top quark, provides a measure of Γ_t. Using the above inputs from analyses using 5.4 fb^{-1} of data, and applying Bayesian techniques to combine the measurements, D0 obtains $\Gamma_t = 2.00^{+0.47}_{-0.43}$ GeV for $m_t = 172.5$ GeV, in agreement with the SM.[126]

Again, based on multiple inputs, D0 searches for contributions from anomalous

top-quark couplings in 5.4 fb^{-1} of data[127], and, in particular for right-handed vector couplings (f_V^R) or left or right-handed tensor couplings (f_T^L, f_T^R), in addition to the $V - A$ left-handed f_V^L interaction of the SM. This search is performed by combining a measurement of the W helicity in the ℓ+jets and $\ell\ell$ channel[128] with the measurement of the single top-quark cross section.[129] The limits are obtained by setting all but one of the anomalous coupling to zero. W helicity is especially sensitive to f_V^R, while the single top-quark cross section is in particularly sensitive to f_V^R and f_T^L. Using a Bayesian statistical analysis to combine the measurements, D0 sets the following limits: $|f_V^R|^2 < 0.30$, $|f_T^L|^2 < 0.05$ and $|f_T^R|^2 < 0.12$, where no assumptions on $|f_V^L|$ are made.

5. Searches in the Top Sector

Besides the precise understanding of the production and properties of the top quark, where deviations from the SM prediction could indicate physics beyond the SM, a variety of direct searches has also been performed for new signals in the top-quark sector. A broad spectrum of search methods has been developed and applied starting with classical searches for resonant peaks, to more elaborate methods, such as the combination of information from different final states, or the use of multivariate discriminants. In this section, we give a brief overview of the most recent direct searches in the top-quark sector.

5.1. *Classical Searches*

The most common way of searching for a new particle is to look for resonant peaks above a known background in the distribution of a specific variable, such as the $t\bar{t}$ invariant mass. Searches of this kind have been carried out in the $t\bar{t}$ mass spectrum, as well as for fourth-generation $b^{'}$ or $t^{'}$ quarks, and for the stop quark, supersymmetric partner of the top quark.

No $t\bar{t}$ resonances are expected in the SM, but many BSM models such as topcolor assisted technicolor models,[130] predict such resonance. Both CDF and D0 have searched for a narrow resonance X, assuming a width of $\Gamma_X = 1.2\% M_X$, which is smaller than the resolution of the detector. Using events in the ℓ+jets final state, the searches were carried out in spectra that reflect the value of $m_{t\bar{t}}$. The mass variable can be defined either through some kinematic considerations that contain partial information about the escaping neutrino, or by using a kinematic fitter that constrains the jets, the charged lepton and the $\not\!\!E_T$ to the known features of the $t\bar{t}$ hypothesis, and adjusts the energies of the jets within their resolution. The most recent searches for a $t\bar{t}$ resonance extract limits on $\sigma(p\bar{p} \to X) \times B(X \to t\bar{t})$ as a function of M_X in events with at least three jets in 9.45 fb^{-1} of data at CDF and 5.4 fb^{-1} at D0. By considering the benchmark model of topcolor-assisted technicolor, a $Z^{'}$ with $m_{Z'} < 835$ GeV is excluded by D0,[131] and $m_{Z'} < 915$ GeV by CDF,[132] both at 95% CL. In addition, D0 shows that the limits do not depend

on the couplings of the $t\bar{t}$ resonances, i. e. whether they are purely axial-vector (A), vector (V), or SM-like (V-A). CDF also considers alljet events, where the reconstruction of the correct invariant mass from a resonant contribution is diluted by the large number of possible jet combinations. CDF uses the ME approach to calculate per-event probability densities to minimize the impact of the large background, and, following event selection based on a NN, searches for $t\bar{t}$ resonances in 2.8 fb^{-1} of data, resulting in an exclusion of $Z^{'}$ with $m_{Z'} < 805$ GeV at 95% CL.[133] CDF performs another search for $t\bar{t}$ resonances in a search for a massive vector color-octet boson (e.g., a massive gluon) in the ℓ+jets final state in 1.9 fb^{-1} of data, setting limits on the coupling strength for different masses m and Γ/m ratios.[134]

Exploring models that can accommodate the anomalous A_{FB} results, CDF has performed a first search for top-quark+jets resonances, seeking signs for the production of a new heavy particle (decaying into $\bar{t}q$) in association with a top quark. In 8.7 fb^{-1} of data, the study selects events with one lepton, $\not\!\!E_T$ and at least five jets and reconstructs the mass of the tj system. Finding data to be consistent with the SM expectations, 95% CL upper limits are determined on the production cross section for different possible masses of the new particle.[135]

Because the extension of the SM to a fourth generation, with massive up-type $t^{'}$ and down-type $b^{'}$ quarks remains a distinct possibility, both collaborations have searched for $t^{'}$ pair production, assuming $t^{'} \to Wq$ decays. CDF performs parallel searches for all the down quarks in $t^{'}$ decays (d, s or b), while D0 assumes just a b-quark as a possibility. Since the $t^{'}$ is expected to have a mass $m_{t'} > m_t$, the search strategy is based on looking for events with larger fitted Wb masses and a larger scalar sum of the p_T values of the lepton and jets than expected in SM $t\bar{t}$ decays. The search is performed in the ℓ+jets final state, containing at least four jets, of which, for D0, at least one is an identified b-jet candidate. The latest upper limits on $\sigma(p\bar{p} \to t^{'}\bar{t}^{'})$ at the 95% CL. as function of $m_{t'}$, are extracted using 5.3 fb^{-1} of data at D0 [136] and 5.6 fb^{-1} at CDF,[137] resulting in $m_{t'} > 285$ GeV and $m_{t'} > 358$ GeV for $t^{'} \to Wb$ decays, respectively, and $m_{t'} > 340$ GeV for $t^{'}$ decays into a W boson and any SM down quark for CDF. CDF also searches for a massive fourth-generation $b^{'}$ quark, decaying into a W-boson and a top quark. Again, using ℓ+jets events, considering the scalar sum of just the jet-p_T values, which is sensitive to a $b^{'}$ signal in events with jets of large p_T and large jet multiplicity, CDF, using 4.8 fb^{-1} of data, excludes a $b^{'}$ with mass $m_{b'} < 372$ GeV at 95% confidence.[138]

The SM particles describe only $\approx 4\%$ of the energy content of the universe and the rest consists of dark energy and dark matter. Possible candidates for dark matter (DM) could be long lived, weakly interacting massive particles (WIMPs),[139] for example, such as the lightest supersymmetric particle, the neutralino. Recently, CDF performed a search for dark matter in the top-quark sector. CDF investigates pair production of some unknown partner of the top quark, T, where T decays into a top quark and a stable, neutral, weakly interacting particle (A_0). The search

strategy relies on using the $t\bar{t}$ signature with large $\not\!\!E_T$ and a large transverse mass of the lepton and $\not\!\!E_T$ system in ℓ+jets events. No deviations from the SM are observed by CDF, and upper limits are reported on $\sigma(p\bar{p} \to T\bar{T}) \times B(T\bar{T} \to tA_0\bar{t}A_0)$.[140] CDF also searches for dark matter in the $t\bar{t}$ final state in ℓ+jets events, where the dark matter is produced through an unknown fourth generation $T^{'}$ quark that decays into a top quark and a dark matter candidate X. Using 4.8 fb^{-1} of data, CDF excludes $T^{'}$ masses $m_{T'} < 360$ GeV for masses of $X < 100$ GeV.[141] A search for the same process is also performed in the alljets channel using 5.7 fb^{-1} of data, increasing thereby the range of exclusion to $m_{T'} < 400$ GeV for masses of $m_X < 70$ GeV.[142] The analysis strategy focuses again on the spectrum in transverse mass of the leptonically decaying W boson, that acquires a broader spread in the signal due to the large $\not\!\!E_T$ contributed by the dark-matter candidate in the ℓ+jets channel. The value of $\not\!\!E_T$ divided by the square root of the total observed energy is used in the analogous analysis of the alljets final state. Using a similar strategy, a first search for production of DM in association with a single top quark at hadron colliders was performed at CDF using 7.7 fb^{-1} of data.[143] Utilizing the production mode $t+DM \to Wb+DM$, with the W boson decaying exclusively into $q^{'}\bar{q}$, the $\not\!\!E_T$ corresponds to the p_T carried away by the DM particle. Finding the data consistent with SM expectations, limits are determined on the production cross section as function of the mass of the dark matter candidate.

Supersymmetric extension of the SM predicts the existence of a scalar partner of the top quark, the stop quark ($\tilde{t}$). CDF and D0 search for the production of a $\widetilde{t\bar{t}}$ quark pair, where each stop decays into a b quark and a chargino (χ_1), and the chargino into a W-boson and a neutralino (χ_0). The neutralinos leave the detector without interacting, giving rise to larger $\not\!\!E_T$ in the stop-pair signal than expected for $t\bar{t}$ events. CDF searches for such events in the dilepton final state using 2.7 pb^{-1},[144] where the $m_{\tilde{t}}$ is reconstructed to discriminate signal from SM background. D0 searches in the ℓ+jets final state using 0.9 fb^{-1},[145] where a multivariate discriminant is defined on the basis of several variables. Neither search shows any signal, and limits are set on the $m_{\tilde{t}}$ for different choices of m_{χ_1}.

5.2. *More elaborate Methods*

As in the example of the search for $\widetilde{t\bar{t}}$ production, where the strategy changed from a direct search for a resonant peak to a more indirect method, other search strategies have also been developed for BSM searches, such as searches for $W^{'}$ bosons, flavor-changing neutral currents (FCNC), and charged Higgs bosons.

Many models beyond the SM contain additional charged $W^{'}$ bosons. Searches in the single top-quark channel are performed for $W^{'} \to tb$ decays, with both left and right-handed coupling to fermions. The first search at D0,[146] using 0.9 fb^{-1}, and at CDF,[147] using 1.9 fb^{-1}, focussed on finding a $W^{'}$ with SM-like couplings, looking for a peak in the invariant mass spectrum of the decay products. A more recent search by D0 in 2.3 fb^{-1} of data explores a multivariate analysis, where

several variables are combined to form a discriminant, with the $W^{'}$ signal trained relative to backgrounds from the SM, assuming different couplings of the $W^{'}$ to the fermions.[148]

No contributions from FCNC are expected at lowest level in the SM. Consequently, observing such effect would indicate the presence of physics beyond the SM. Both CDF and D0 searched for effects from FCNC in the top-quark sector. At CDF, a search for $t \to Zq$ decays was performed in $t\bar{t}$ events in final states that contain two leptons from the decay of the Z-boson and a $t \to Wb \to q^{'}\bar{q}$ decay. After splitting the sample into subsamples according to their content of b-jets, a χ^2 variable is constructed to search for a peak in the $\ell^+\ell^-$ mass spectrum in 1.9 fb^{-1}.[149] At D0, the search for FCNC in $t\bar{t}$ events uses 4.1 fb^{-1} of data, in events with three leptons in the final state, one from the decay of the W-boson and two from the $Z \to \ell^+\ell^-$ decay. For this search, an excess is sought in the spectrum of the nominal reconstructed top mass, as well as in the scalar sum of the p_T of the decay remnants of the candidate top quarks, resulting in limits of $B(t \to Zq) < 3.2\%$ at 95% CL.[150] While the searches for FCNC in $t\bar{t}$ events relies mostly on one or two variables, D0 also performed a search for the decay $t \to gu$ and $t \to gc$ in single top-quark events using a multivariate discriminant. Exploring 2.3 fb^{-1} of data, the dedicated training of FCNC signal relative to the SM background yields limits of $B(t \to gu) < 2.0 \times 10^{-4}$ and $B(t \to gc) < 3.9 \times 10^{-3}$ at 95% CL.[151] Using 2.2 fb^{-1}, CDF also searches for FCNC in single top-quark events, resulting in $B(t \to gu) < 3.9 \times 10^{-4}$ and $B(t \to gc) < 5.7 \times 10^{-3}$ at 95% CL.[152]

While decays of the top quark in the SM almost always happen into a W-boson and a b quark, other models predict the extension of the Higgs sector by at least one doublet. In these models a charged Higgs boson ($H^{\pm}$) that is lighter than the top quark is expected to exist, giving rise thereby to the possibility of $t \to H^+b$ decays. Both collaborations perform a variety of searches for light charged Higgs bosons, that consider H^+ decays into $\tau\nu$, $c\bar{s}$ or a CP-odd neutral Higgs boson (A). Assuming pure $H^+ \to c\bar{s}$ decays, CDF searches in the ℓ+jets channel in 2.2 fb^{-1} of data for a peak in the invariant mass of the jets without b-tags.[153] CDF also considers the possibility of $H^+ \to W^+A$ decay, searching for a deviation in the distribution of isolated tracks of low p_T from the decay of the τ leptons in 2.7 fb^{-1}.[154] Another search strategy for light charged Higgs bosons relies on the expected differences in distributions of events in the different classes of final states, resulting from different branching fractions compared to predictions from just the SM. At D0, a comparison of the number of events in the ℓ+jets, dilepton, and τ+lepton final states is performed using 1.0 fb^{-1} of data, assuming $B(H^+ \to \tau\nu) + B(H^+ \to c\bar{s}) = 100\%$.[155] A similar search is available from CDF for 0.2 fb^{-1} of data.[156] None of the searches show a deviation from the SM, and upper limits on $B(t \to H^+b)$ are set as function of m_{H^+}. At D0, the possibility of heavy H^+ bosons is explored through $H^+ \to t\bar{b}$ decays. Using 0.9 fb^{-1} of data, a multivariate discriminant is trained for H^+ signal relative to SM background in single top-quark

events, resulting in upper limits on $\sigma(H^+ \to t\bar{b})$ for several 2HDM scenarios.[157]

In Section 4.1, the measurement of the difference in masses of the top and anti-top quark has been described, which is a test of the CPT theorem. D0 has recently explored the possibility of the violation of Lorentz invariance in the top-quark sector. The issue of CPT invariance is related to Lorentz invariance, as violation of Lorentz invariance leads to the violation of CPT in particle interactions.[158] For this search, the time stamp is extracted for each luminosity block of recorded data to search for a dependence of the $t\bar{t}$ cross section in the ℓ+jets final state on sidereal time in 5.3 fb^{-1} of data. No indication for a time dependent $\sigma_{t\bar{t}}$ is observed, resulting in the first constraints on the standard-model extensions for violation of Lorentz invariance in the top-quark sector.[159]

6. Summary

Since the discovery of the top quark in 1995 by the CDF and D0 collaborations, a wide range of measurements and searches in the area of top-quark physics have been carried out. By now, most of the available Tevatron data has been analysed, providing strong evidence that the top quark is indeed the particle expected in the SM. Measurements such as the production angular asymmetry of t and $\bar{t}$, $t\bar{t}$ spin correlations, the mass of the top quark and the production cross sections represent an important legacy of the Tevatron. The $p\bar{p}$ initial state makes some of the measurements at the Tevatron unique, and complementary to what can be learned from pp collisions at the LHC.

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